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2. Patent application number *(The Patent Office will fill in this part)* 0424271.5

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Powerlase Limited
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Link 10, Napier Way
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West Sussex, RH10 9RA

Patents ADP number *(if you know it)* 8302333001.

If the applicant is a corporate body, give the country/state of its incorporation: United Kingdom

4. Title of the invention

5. Name of your agent *(if you have one)*

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

Kilburn & Strode
20 Red Lion Street
London
WC1R 4PJ

Patents ADP number *(if you know it)* 125001

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Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

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Claim(s)	3
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Request for preliminary examination and search *(Patents Form 9/77)*	1
Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(please specify)*	

11. I/We request the grant of a patent on the basis of this application.

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Laser Amplifier

The present invention relates to a solid state laser amplifier, in particular for use with a laser, and more particularly for use external to a laser oscillator cavity.

The use of laser amplifiers comprising a pumped gain medium such as a rod is well known for increasing the optical power emitted from a laser. Amplifiers can be placed at the output of a laser cavity and can provide additional optical power. Applications include pulsed or continuous wave (CW) laser, whereby the increased power output available from amplification may be used for any number of laser applications such as thin-film ablation, surface cleaning applications, or any application where high average power is required. However to provide effective amplification it is necessary that efficient coupling of light from the laser to the amplifier takes place.

The coupling requirement must take into account thermal lensing effects which can reduce beam overlap and hence gain extraction in a laser rod. The thermal lens of an amplifier module depends on the rod diameter, the total absorbed pump power and the length of the rod. The thermal lens arises as a consequence of a thermal gradient from the rod centre to the cooled edge that leads to a radius dependent change to the refractive index. A strong thermal lens has a focal length of a few centimetres to several tens of centimetres.

Various solutions have been proposed for efficiently coupling light. One example, described in US 2004/0028108, relates to a method of coupling laser light into an amplifier using relay-imaging optics. Figure 1 illustrates a

schematic of a prior art arrangement required to relay image from a source gain medium into a target amplifier medium. In this example a unit magnification telescope 10 comprising lenses 12, 14 is used to image each point in space on the source 16 to the corresponding point in the amplifier 18. The telescope 10 may magnify or de-magnify in order to account for differences in sizes of gain media when compared to the laser source. A further method described in US 5,237,584, uses curved cavity mirrors to image one amplifier module to the next.

However, several problems exist with existing relay imaging techniques. Using additional optics increases the number of components, and the possibility of formation of intermediate foci that can damage the optical components. Moreover, additional optics require precise alignment to achieve maximum coupling efficiency.

The invention is set out in the claims. Because of the profiling of the gain medium ends the beam passes through the gain medium and achieves a high extraction efficiency because the beam volume overlaps well with the gain volume inside the rod. This allows simple and efficient scale up adding additional amplifier modules. Each additional gain module adds ~200W to the output. Moreover, the beam quality M^2 increases by 1.5 for each additional amplifier.

Embodiments of the invention will now be described, by way of example, with reference to the following drawings, of which;

Figure 1 is a schematic view of a relay-image system embodying the prior art;

Figure 2 is a comparison of gain overlap between low M^2 and high M^2 beams;

Figure 3a is a schematic view of good gain overlap with zero thermal lens;

Figure 3b is a schematic view of poor gain overlap with strong thermal lens;

Figure 3c is a schematic view of maximised gain overlap with thermal lensing such that the beam passes through the gain medium symmetrically;

Figure 4 is a diagram of a pumped amplifier module;

Figure 5 is a schematic view showing thermal lens compensation;

Figure 6 shows the principal design criteria for the present invention;

Figure 7 shows a laser module for use in conjunction with the invention;

Figure 8 shows operation of multiple amplifier modules in a mirror-image configuration; and

Figure 9 shows multiple amplifier modules.

In overview the present invention uses an amplifier rod medium with curved ends to act as lensing elements to collect emission from a laser oscillator. The combination of thermal lens and curved rod ends produces a lensing effect which allows light to be directly coupled from a laser without the need for additional optics. In addition, variation of the input pump power allows for control of the thermal lens formed within the amplifier rod.

Fig. 4 shows an amplifier module comprising a solid state Neodymium doped YAG (Nd:YAG) gain medium (100) according to the invention. The gain medium is optically side pumped, by laser diode bar emitters (106), in a pump direction orthogonal to the gain medium longitudinal axis. The pump source and gain medium are cooled in order to remove excess heat. Water cooling is common but any appropriate method as known in the art may be used the laser rod 100 in the gain module has concave ends (102,

104). This adds a negative lensing component that modifies the positive thermal lens induced inside the laser rod. A strong thermal lens occurs as a consequence of the high pump powers required to produce the high output powers. The overall effect of the thermal lens and rod-end curvatures provides a weakly positive lens that ensures the laser cavity operates in a stable configuration. A laser of the type described in co-pending application no. GB0403955.8, incorporated here by reference is suitable, for example.

As shown in Fig. 7, the amplifier gain module (712) is added after a laser gain module (700), which is preferably a mirror image of the laser gain module.

The amplifier module 712 receives an input laser beam from the laser oscillator (700) part of the system as shown in figure 7 is formed by a standard laser. This comprises a Fabry-Perot-style cavity (formed by two flat mirrors (702,704)) with a gain module (706) and two acousto-optic (AO) Q-switches (708,710) between them. The Fabry-Perot cavity is formed by a high reflector mirror (702) and output coupler mirror (704). The gain module (706) provides the gain for the cavity and loss modulation is provided by a pair of orthogonal acousto-optic modulators (AOM's). When the AOM's are fully on (high power RF signal applied), they eject light from the cavity providing a loss. This allows the gain in the cavity to build up to a high level. When the AOM's are turned off, the cavity is allowed to lase and the stored gain is released as a large pulse. This process is repeated many thousands of times a second producing pulses with both a high peak power and a high average power. This configuration is capable of delivering output powers of more than 400 W at repetition rates between

3 and 50 kHz with pulse durations between 30 and 200 ns. The beam quality of the system (M^2) is approximately 22.

The light emitted by the laser oscillator couples naturally into the amplifier gain module as the photons effectively do not see the output coupler mirror; they pass through the additional gain module as if it were another intracavity module, as discussed in more detail below and shown in Fig. 8, where multiple replicated cavities 900, 902 are shown.

As discussed above the ends of the amplifier medium (102, 104) are curved concavely to provide a lensing component (in most cases this profile will be a concave radius of curvature in the order of tens of centimetres). In the embodiment shown, the laser and amplifier modules have the same dimensions and provide the same amount of lensing at corresponding same pump power, therefore producing the same amount of lensing. At the requisite pumping power, the combination of positive thermal lensing and the negative rod end lensing from produces overall, a weakly positive lens sufficient to sufficiently couple the maximum amount of light into the amplifier without over or under filling the rod. Ideally the amplifier is a mirror image of the laser gain medium.

The curvature of the rod ends is designed to provide optimum coupling and be understood from the following discussion of a simple model for typical laser amplifiers that use a number of input parameters to predict the output. The following equation 1 defines such a model in terms of fluences (defined as pulse energy divided by beam area in joules per square centimetre):

$$\Gamma_{out} = \Gamma_s \ln\left\{1 + G_0\left[\exp\left(\frac{\Gamma_{in}}{\Gamma_s}\right) - 1\right]\right\} \qquad \textit{Equation 1.}$$

where Γ_{out} is the output beam fluence of the amplifier, Γ_s is the saturation fluence of the gain medium, Γ_{in} is the input beam fluence and G_0 is the small signal gain. The small signal gain depends on the following:

$$G_0 \sim P_P \eta_T \eta_E \qquad \textit{Equation 2.}$$

where P_P is the total input pump power; η_T is the transfer efficiency from pump power to stored energy in the rod; and η_E is the extraction efficiency.

The small signal gain determines how much power the amplifier delivers for a given input power, beam size and repetition rate. The higher the repetition rate, the lower the gain available per pulse. The transfer efficiency (η_T) is a consequence of the quantum defect of the gain medium and of the design of the pump chamber surrounding the rod. The extraction efficiency (η_E) is determined by how well the input beam overlaps with the gain volume in the laser rod. Extraction efficiency is also affected by the quality of the input beam, known as M^2.

To illustrate the effect of M^2 on the extraction efficiency of the amplifier, a gain volume in the laser rod with a uniform distribution is illustrated in figure 2. The gain profile is shown by the solid curve and the dashed curves represent the beam profile as a function of distance from the centre of the rod (r). The curve on the left shows how a beam with a low M^2 overlaps poorly with the gain profile leaving lots of unused gain after the beam has passed through the amplifier. The curve of the right shows how a beam with a high M^2 overlaps well with the gain profile extracting the available gain more efficiently. From this illustration it is easy to appreciate that the higher the M^2, the more efficiently the gain is extracted.

To illustrate the importance of beam overlap and the effect of thermal lensing, it will be seen that where a collimated input beam is sent into a gain module 20 with zero thermal lens (see Figure 3**a**), the beam passes through the gain medium and achieves a high extraction efficiency because the beam volume overlaps well with the gain volume inside the rod. The maximum extraction efficiency is in this case limited by the M^2 of the input beam, as mentioned above.

However, pumping the amplifier hard, to produce the desired increase in output powers (approximately 200W per additional amplifier) produces a positive thermal lens effect in the amplifier gain medium.

When a strong thermal lens is present shown by the dashed curved line in figure 3b, the collimated input beam overlaps poorly with the gain volume because the beam diameter quickly reduces as it passes through the rod. Maximum overlap (for a beam with a given M^2) is achieved when the input beam passes symmetrically though the gain medium. This is especially true when there is more gain around the centre axis of the rod than around the edges, as is most commonly the case.

Accordingly, to pass the beam though the gain module symmetrically, additional beam conditioning optics are required. The beam conditioning optics modify the divergence of the input beam so that it appears there is a beam waist in the position marked "W" in Figure 3**c**, close to the amplifier module 24. The stronger the thermal lens, the closer the waist needs to be to the amplifier module to pass through it symmetrically.

The lensed surfaces (102, 104) of the amplifier medium (100) are achieved by placing a radius of curvature (RoC) on the end of the rod. In the special

case where there is zero thermal lens effects in the gain medium, the RoC may be convex (positive lens) in order to collimate a diverging beam through the rod. In general, a concave RoC will be used on the end of the rod to provide a positive lensing component to balance the positive thermal lens. Figure 5 shows how a gain medium (51) exhibiting strong thermal lensing (52) may be optimally coupled by using a concave RoC (53) on the input side of the laser rod. The RoC on the exit side of the rod may be any curvature suitable for subsequent use of the output beam. In Figure 5, the exit RoC is the same as the input.

Accordingly an appropriate RoC must be determined for the desired operating conditions.

Firstly the degree of thermal lensing is identified. The thermal lens of a particular amplifier module can be determined by shining a HeNe laser through a rod with flat ends when it is fully pumped by the pump source. The HeNe will be focused at a point equal to the thermal focal length of the rod at 633nm. An equivalent lens focal length can then be calculated for the lasing wavelength of the amplifier module.

Once the thermal focal length of the amplifier module laser rod is known (f_{th}), the rod-end radius of curvature can be calculated for given input beam parameters using a thin lens model. Figure 6 shows how an ideal input beam 602 optimally overlaps with the gain volume 600 in the rod (solid beam). The ideal input beam 602 has a diameter at the input rod end 604 associated with it (D_i). The beam diameter and divergence of an arbitrary input beam 606 (dashed beam) must be matched in order to achieve optimum extraction efficiency. The beam diameter at the rod input can be calculated approximately by the following equation:

$$D_i = D_R - \frac{D_R L_R}{8 f_{th}}$$ *Equation 3.*

where D_R is the rod diameter, L_R is the rod length and f_{th} is the rod thermal focal length. The waist of an arbitrary input beam must be placed a distance d_o from the amplifier module in order that its diameter equals D_i at the input rod end. d_o is defined as follows:

$$d_o = \frac{2 \tan \theta_o}{D_i}$$ *Equation 4.*

where θ_o is the arbitrary input beam divergence half angle. In order to modify the divergence of the arbitrary input beam so that it matches the divergence of the ideal input beam inside the amplifier module, a negative radius of curvature given by the following equation must be placed on the end of the rod:

$$R = \frac{d_o (4 f_{th} - L_R)(n_L - n_{air})}{n_L (4 f_{th} - L_R - 2)}$$ *Equation 5.*

where n_L is the refractive index of the amplifier gain medium and n_{air} is the refractive index of air, both at the laser wavelength. The above equations give an approximate method for calculation of the rod-end radius of curvature required to optimally couple into an amplifier module with a strong thermal lensing component. More complex models can be used, for example using a graded index (GRIN) lens model of the thermal lens rather than the thin lens model used above.

In systems of very high gain, small back reflections from the input surface of the amplifier may upset the performance of the oscillator. In this case, the input surface can be tilted slightly in order that back reflections do not return to the oscillator. The output surface can be tilted in an anti-parallel manner to offset the effects of astigmatism introduced by tilting a curved lensing component.

If the amplifier module is fully pumped, but no input beam is present, the thermal lens will have a slightly (stronger) value. This can be offset by reducing the input pump power to a level that mimics the level when a high power input beam is present. These effects are thermal and therefore apply when the amplifier is pumped but unused for a duration comparable to the thermal equilibrium time of the gain medium (determined by the thermal conductivity and dimensions). Preferably the laser and amplifier are pumped simultaneously.

The amplifier module may be symmetrical and identical to the laser module in the embodiment described above but the radius of curvature of the exit end of the rod may be chosen in a similar fashion to the method above for any required exit image position such that asymmetric and other variations can be accommodated.

The invention gives rise to a number of advantages. Each amplifier module increases the output power by approximately 200W respectively. Multiple amplifiers 910, 912 may be cascaded together as shown in Fig. 9 to produce very high average powers from a laser oscillator source 914 (hundreds of watts to multiple kilowatts) delivered via transport optics 916 to a laser application 918; the only limit being the damage threshold of the laser gain media or coatings used, or self-imposed limits on efficiency defined by the

input beam fluence and the saturation fluence of the gain medium used. The output pulse duration of the emission is unchanged with addition of amplifier gain modules. The output beam quality (M^2) is raised by approximately 1.5 by each additional gain module.

Amplifiers may be applied to a number of different sources including high power (>100 W) pulsed (Q-switched or mode-locked) oscillators in, for example, in a Power Oscillator Power Amplifier (POPA) configuration. They may also be used for continuous wave (CW) oscillators (high and low power); low power (<100 W) Q-switched, mode-locked or CW oscillators; fibre oscillators; picosecond, nanosecond, microsecond or millisecond oscillators and in a range of applications such as thin-film ablation and surface cleaning applications.

It will be appreciated that any appropriate gain medium, pumping scheme or source and cooling scheme can be adopted and that the rod ends can be profiled in any appropriate manner to provide refractive or diffractive (e.g. Fresnel) lenses or GRIN lenses effectively mounted on the ends.

Claims

1. A laser amplifier having:
a laser cavity; and
an amplifying module external to the laser cavity, said amplifying module sharing a common axis of emission with said laser cavity and comprising a gain medium having first and second ends along said axis of emission, whereby at least one of said first or second ends is profiled so as to directly couple light from said laser cavity into said amplifying module.

2. A laser amplifier as claimed in claim 1 wherein one or both of said second ends are profiled to form a lens having a predetermined focal length.

3. A laser amplifier as claimed in claim 1 wherein said laser comprises a gain medium with profiled ends.

4. A laser amplifier as claimed in claims 2 or 3 in which the lens is one of a refractive, diffractive or GRIN lens.

5. A laser amplifier as claimed in claims 3 or 4 wherein said laser gain medium ends are profiled to form a lens having a predetermined focal length.

6. A laser amplifier as claimed in any of claims 3 to 5 wherein said lens of said laser gain medium and said lens of amplifier gain medium have substantially equal focal lengths.

7. A laser amplifier as claimed in any preceding claim whereby said laser gain medium lens and said amplifier gain medium lens are concavely profiled.

8. A laser amplifier as claimed in any preceding claim, wherein said laser and said amplifying medium are pumped simultaneously.

9. A laser amplifier as claimed in claim 8 wherein said laser pump and said amplifying pump have equal power.

10. A laser amplifier as claimed in any preceding claim in which an input surface to the amplifier is tilted.

11. An optical amplifier module comprising a medium having first and second ends, at least one end being profiled to provide a level of lensing at a predetermined operating power, arranged such that, in use, the amplifier can be directly coupled to a laser of predetermined parameters.

12. A module as claimed in claim 11 in which, for an amplifier medium comprising a rod of diameter D_R, length L_R refractive index n_L in air of refractive index n_{air} and thermal focal length f_{th} arranged to receive an input beam from a laser having waist distance d_o from the input rod end, the rod is profiled with a radius of curvature R given by $R = \frac{d_o(4f_{th} - L_R)(n_L - n_{air})}{n_L(4f_{th} - L_R - 2)}$

13. A method of making a laser amplifier module gain medium comprising profiling at least one end thereof to provide a level of lensing at a predetermined operating power, arranged such that in use, the amplifier can be directly coupled to a laser of predetermined parameters.

14. A method of designing a laser amplifier as claimed in any preceding claim comprising identifying a profile as defined in claims 11 or 12.

15. A laser amplifier as described substantially herein with reference to the accompanying drawings.

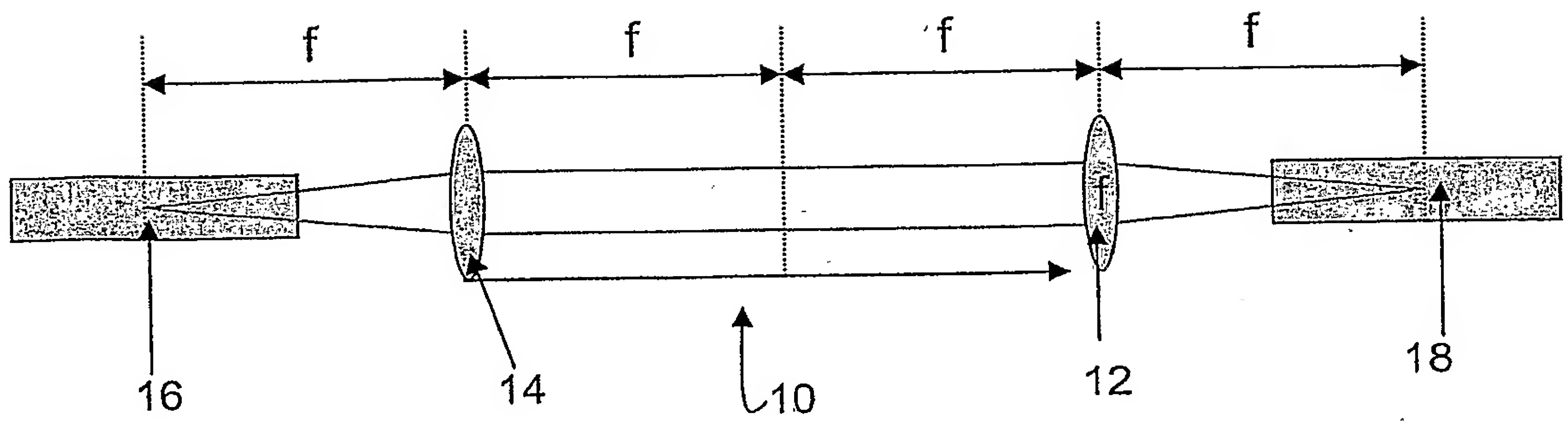


Fig.1

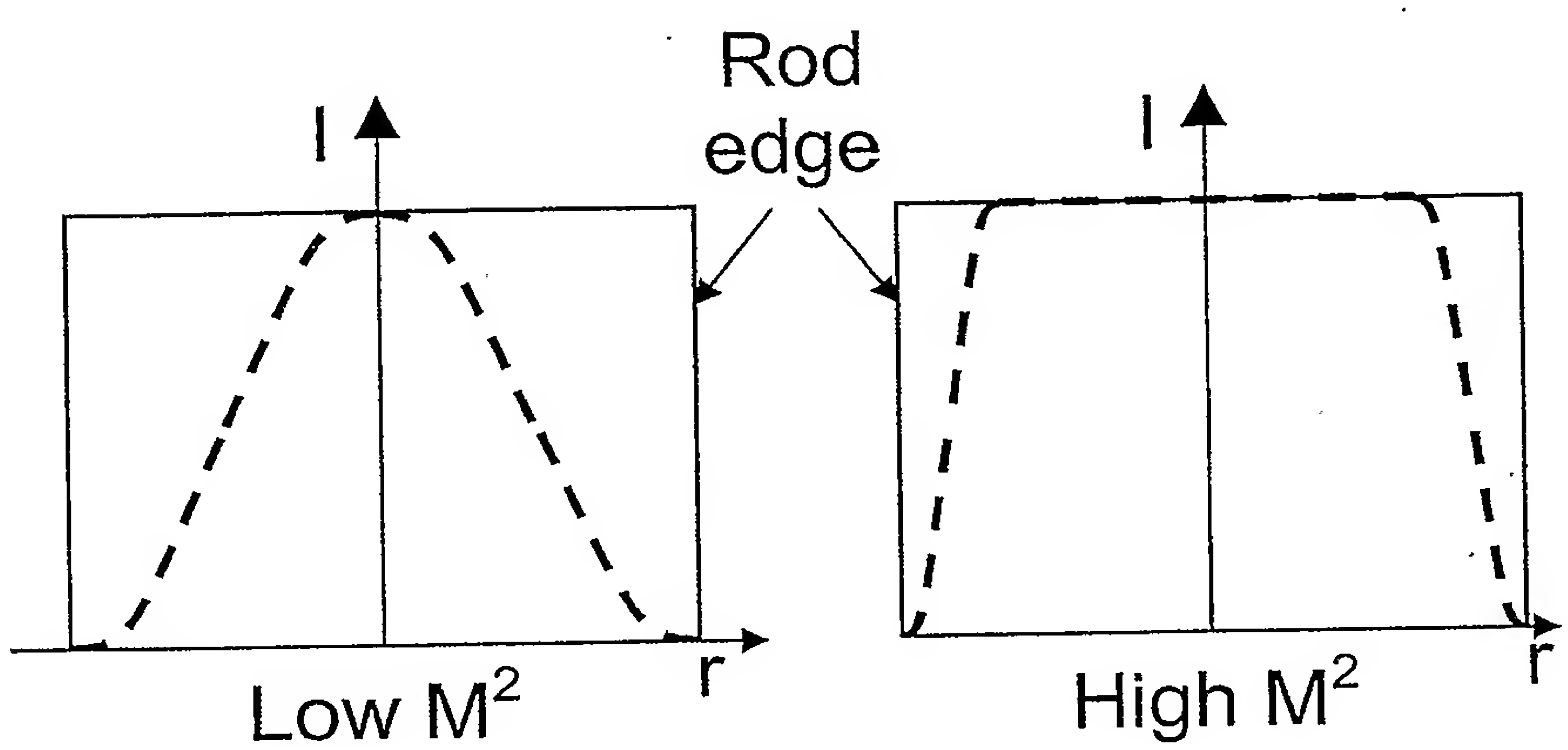
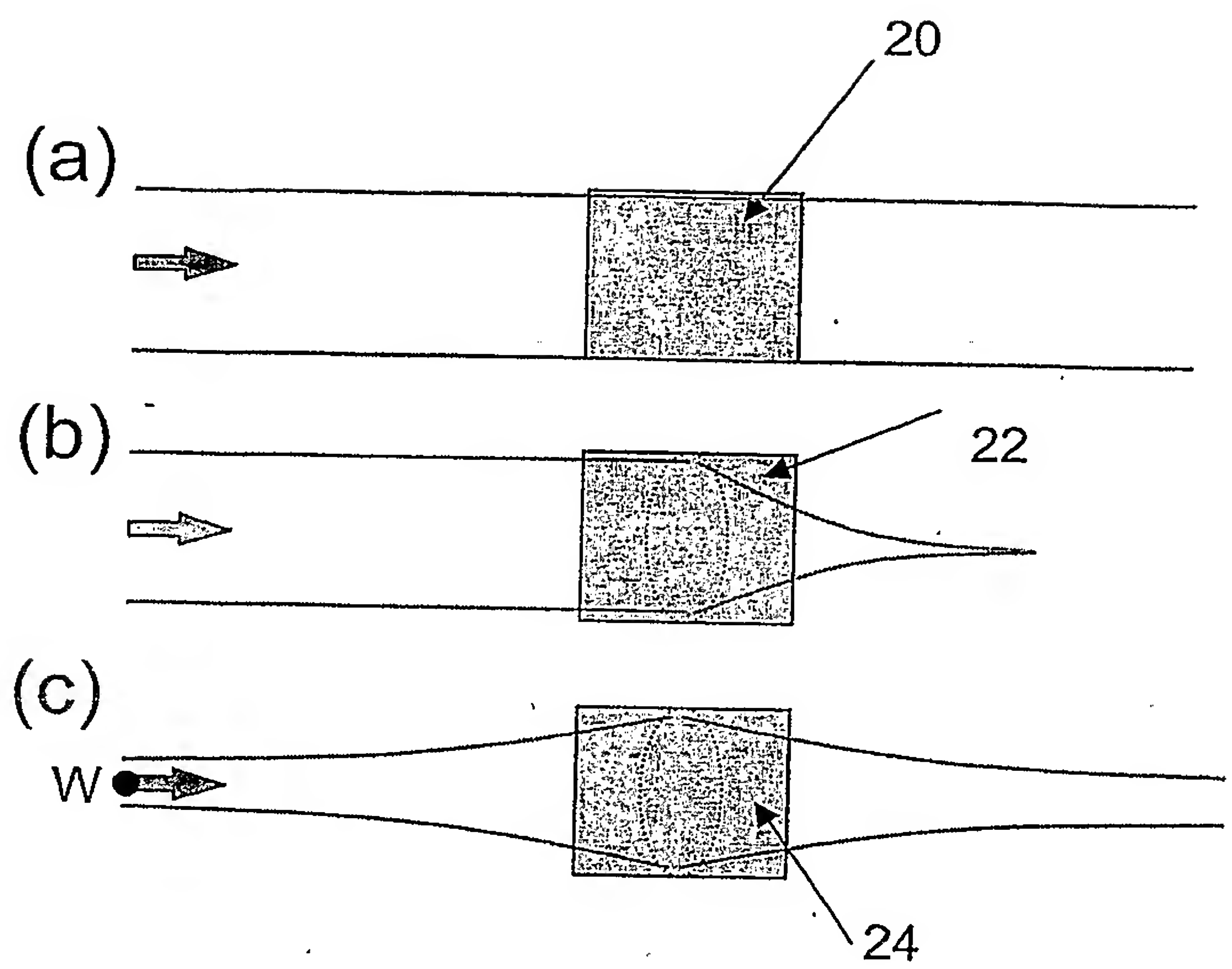
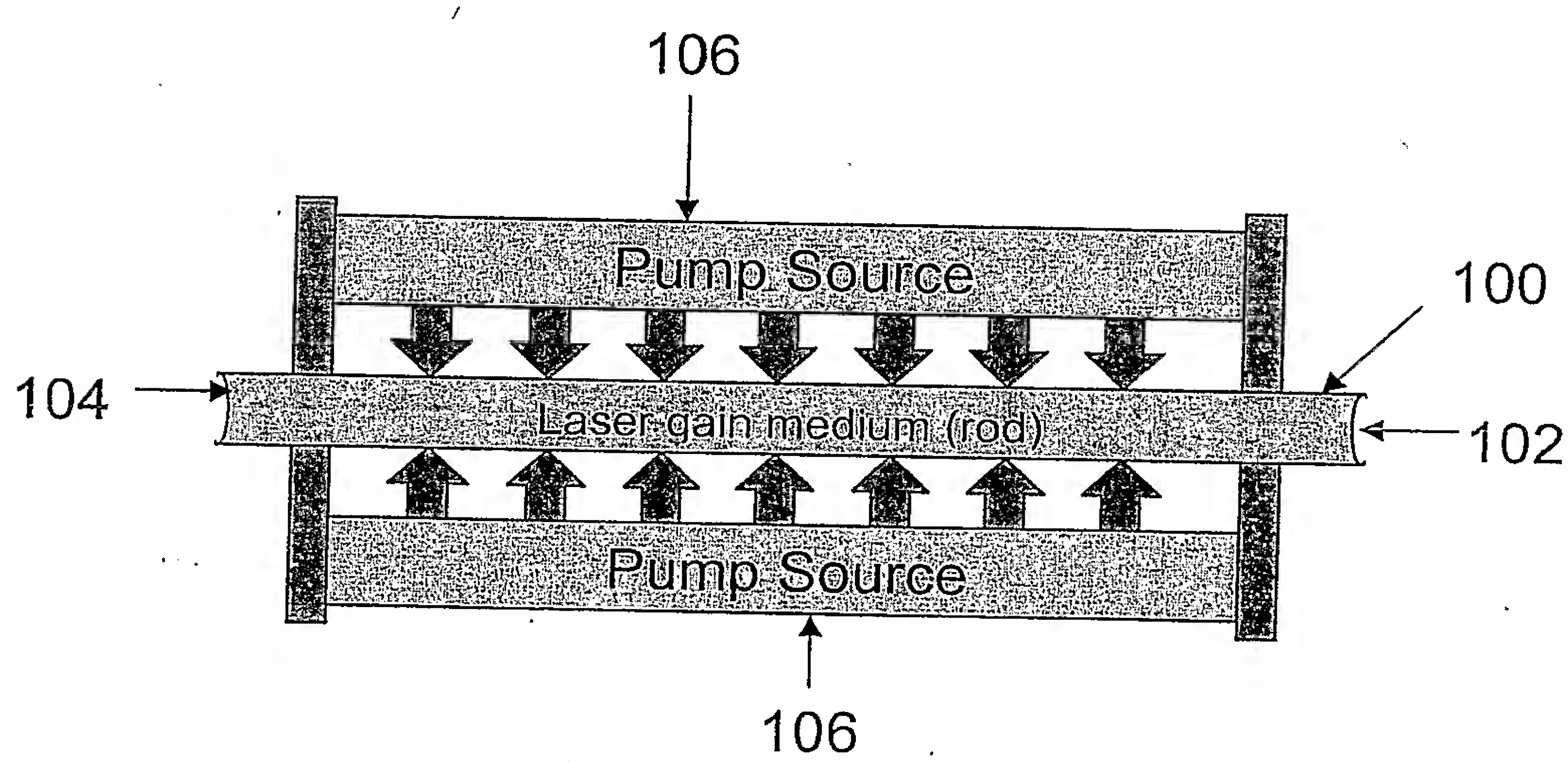


Fig.2



20
(a)
(b)
22
(c)
W
24

Fig. 3



106
Pump Source
100
104
Laser gain medium (rod)
102
Pump Source
106

Fig. 4

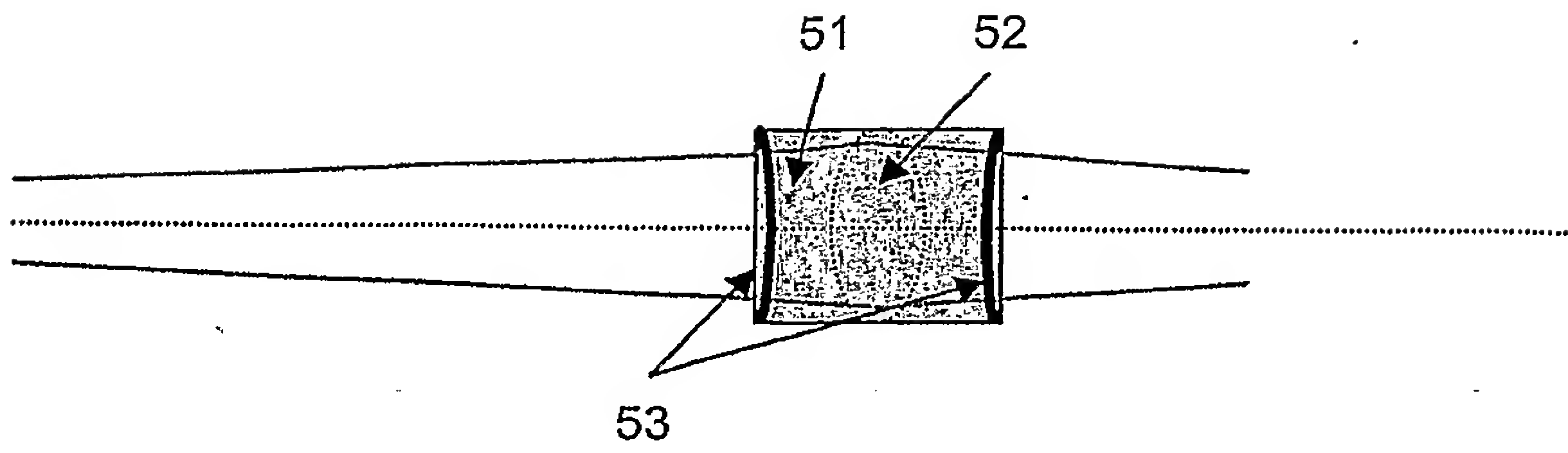

51
52
53

Fig. 5

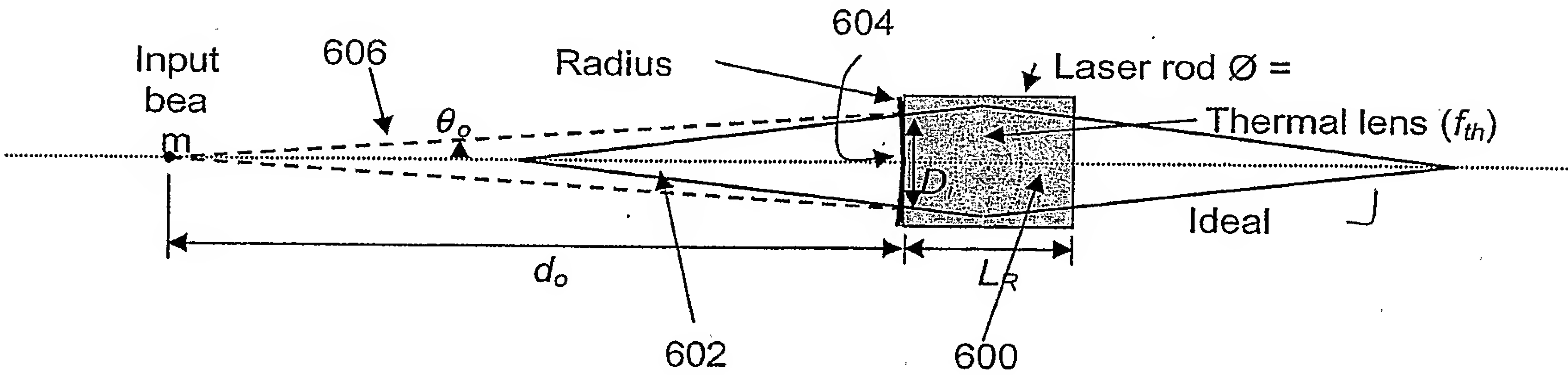

Input
bea
m
606
θ_o
Radius
604
Laser rod Ø =
Thermal lens (f_{th})
D
Ideal
d_o
L_R
602
600

Fig. 6

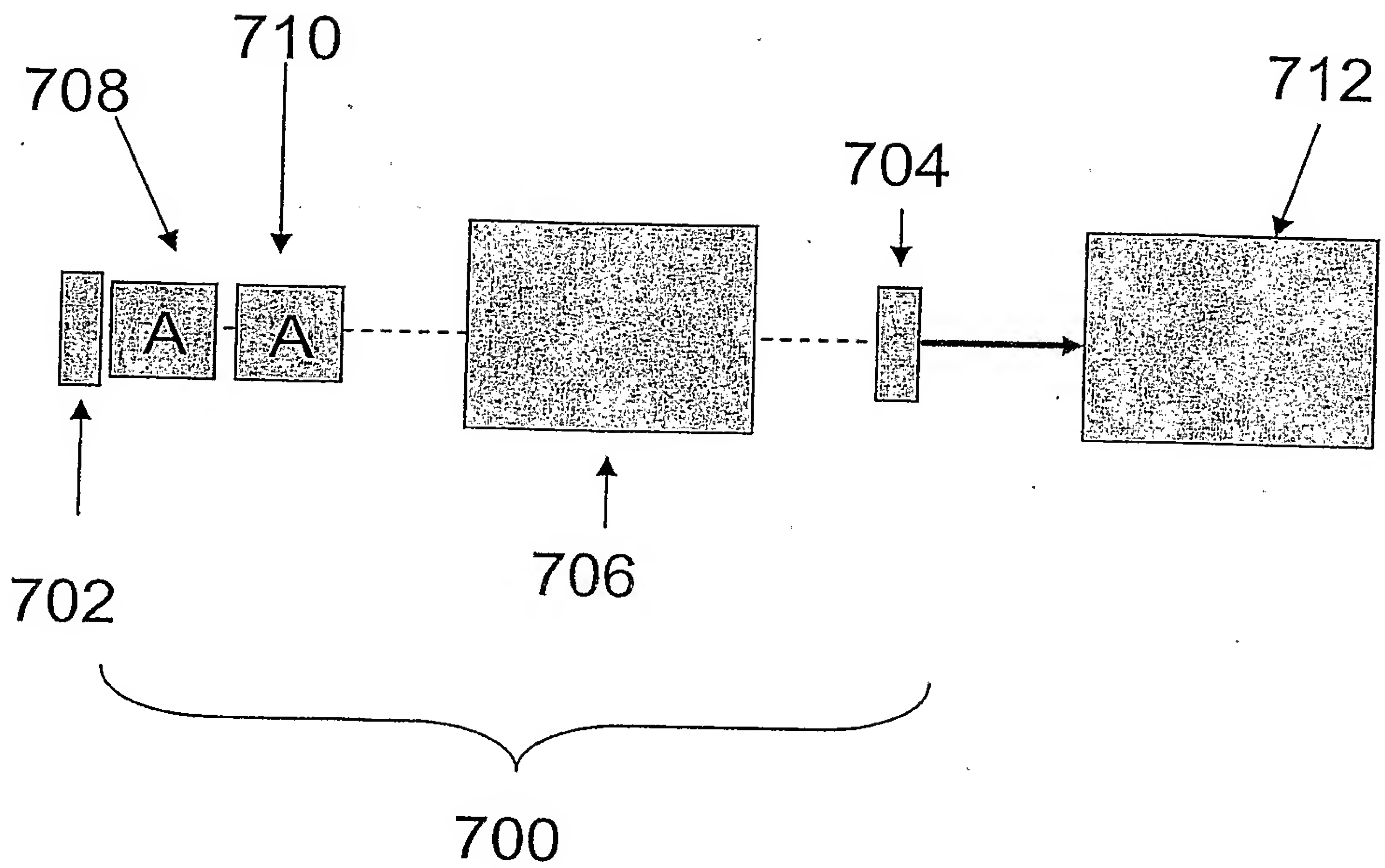


Fig. 7

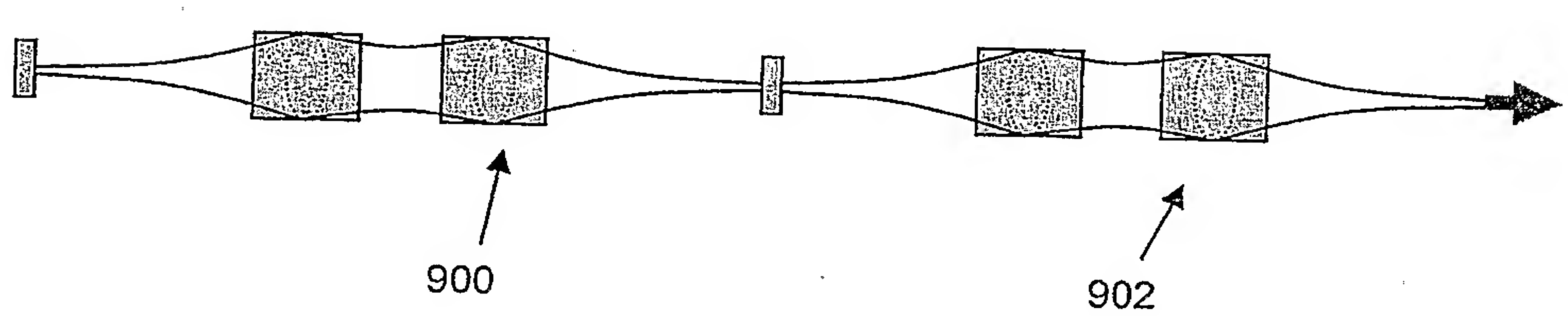


Fig. 8

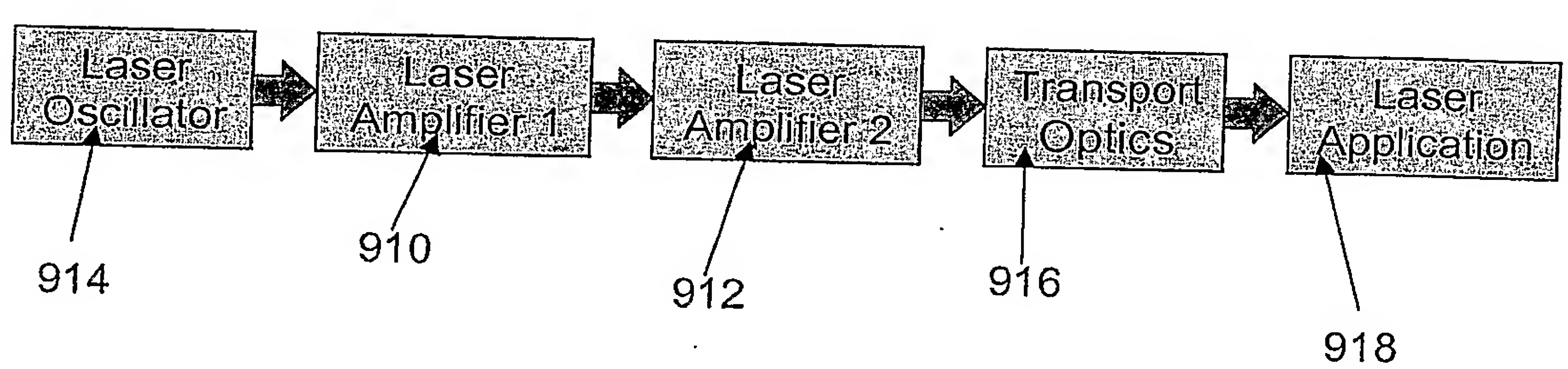


Fig. 9

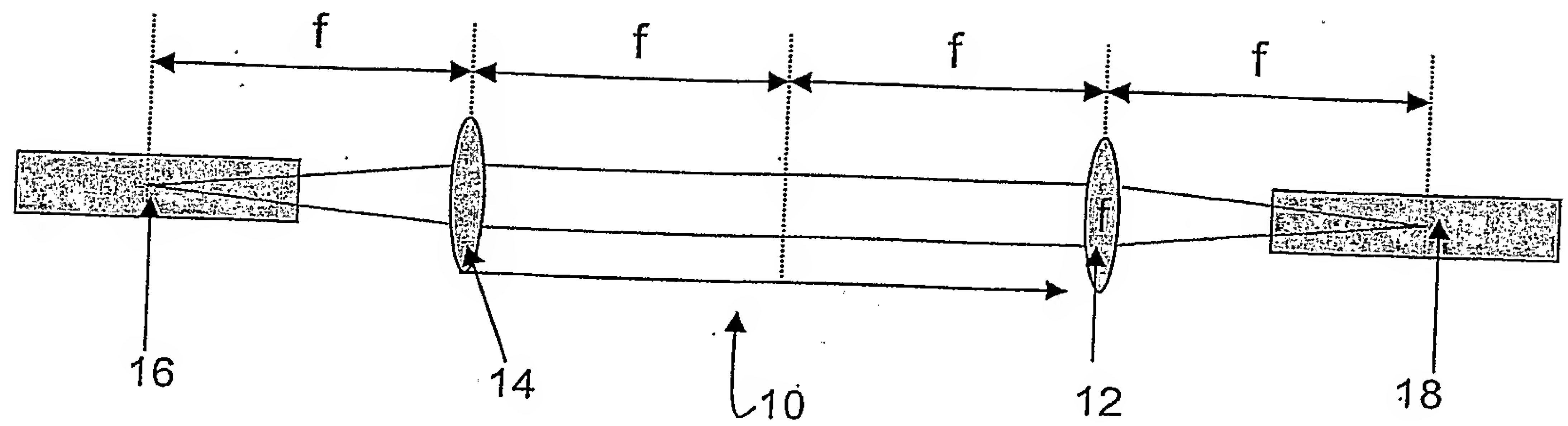


Fig.1

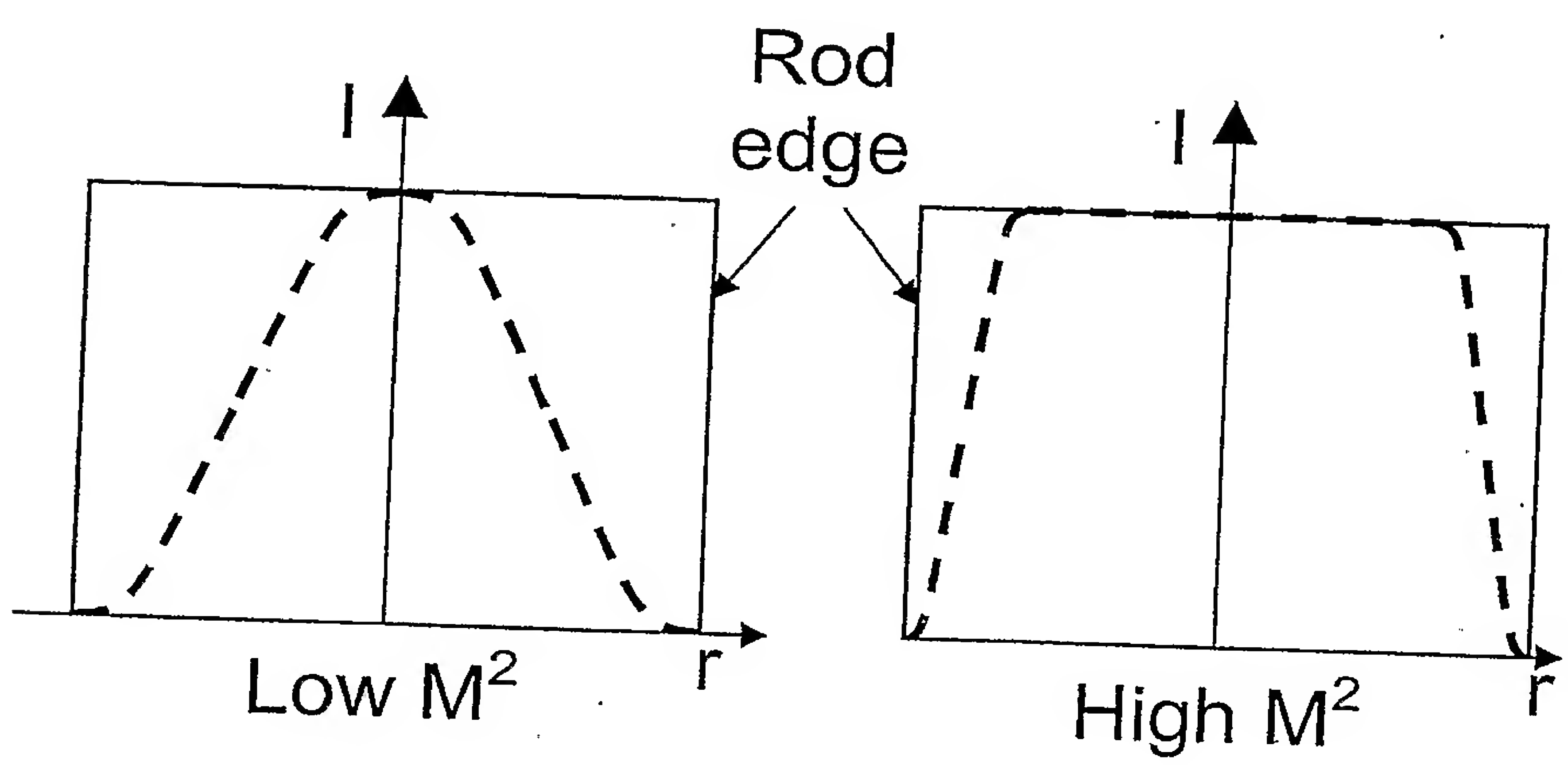


Fig.2

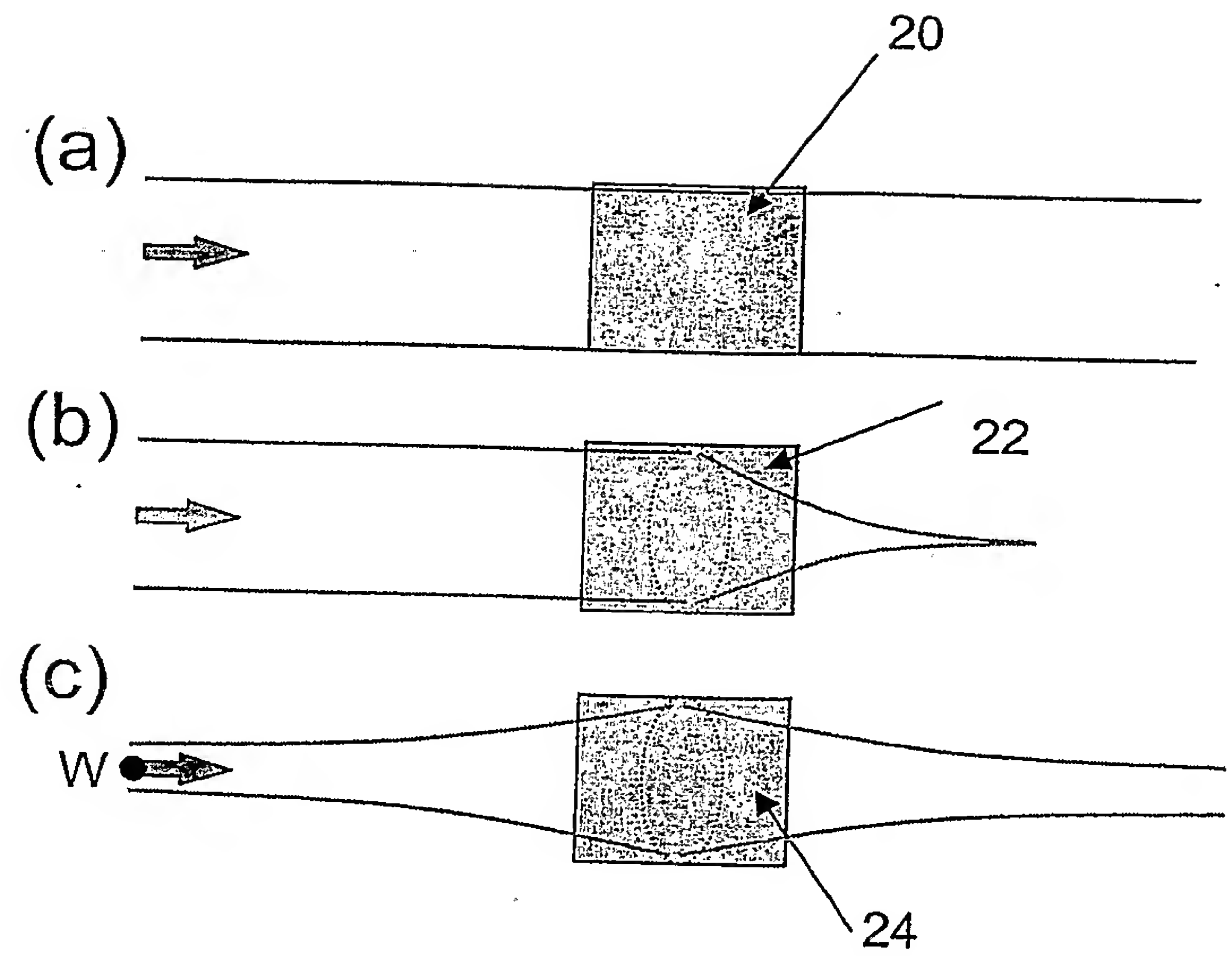

20
(a)
(b)
22
(c)
W
24

Fig. 3

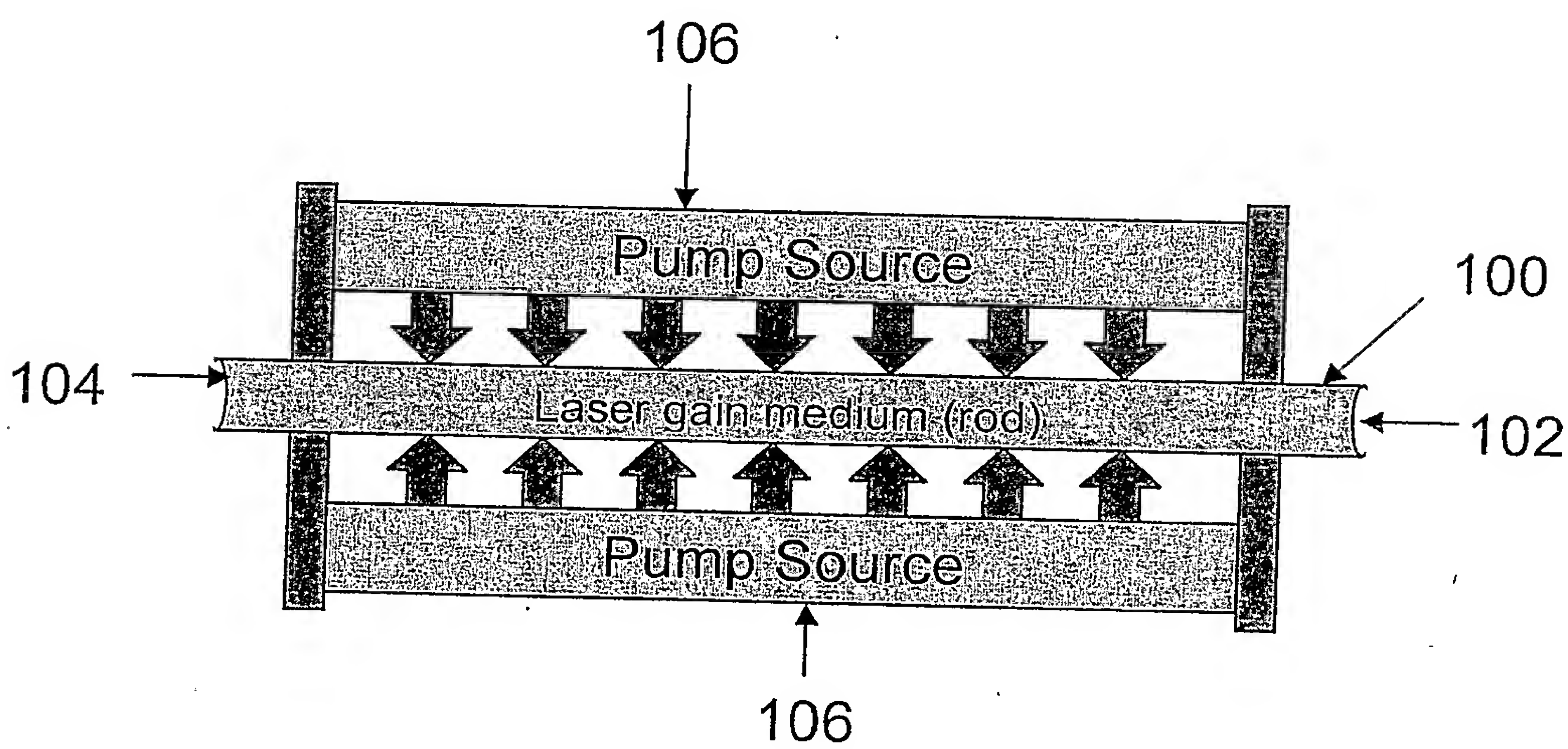

106
Pump Source
100
104
Laser gain medium (rod)
102
Pump Source
106

Fig. 4

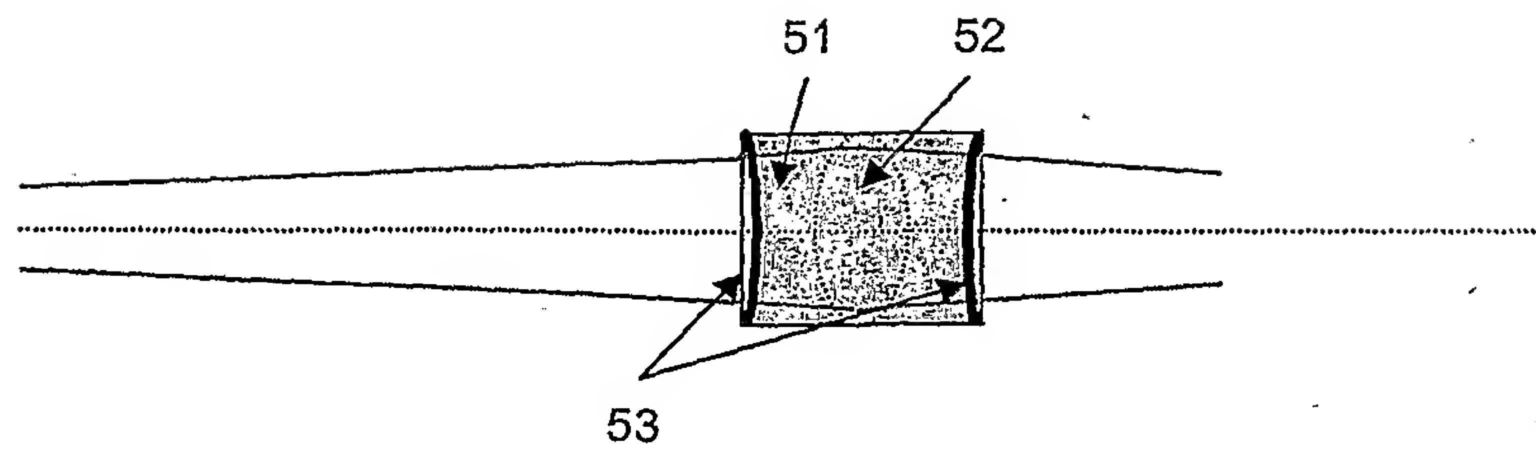

51
52
53

Fig. 5

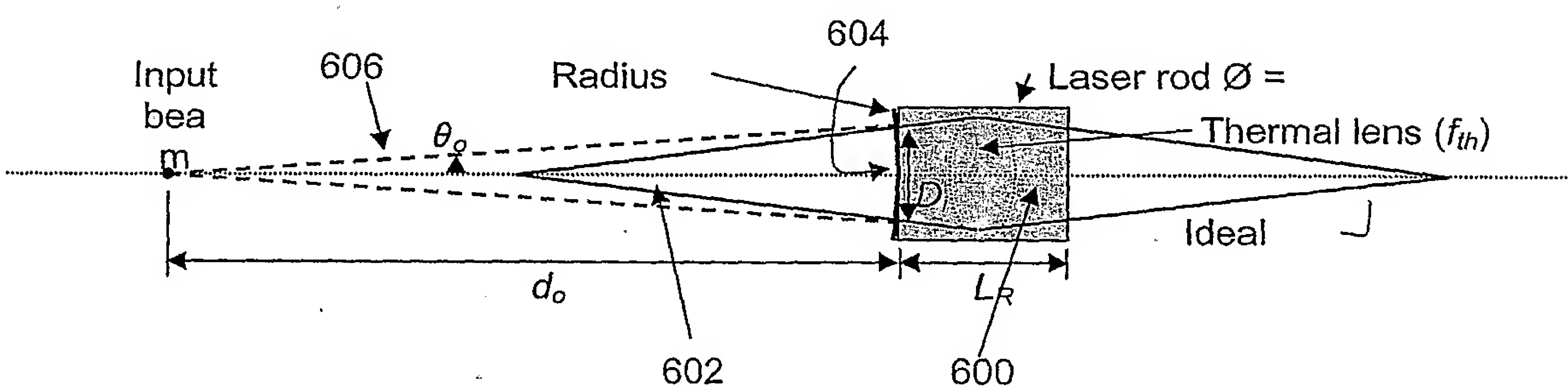

604
Input
bea
m
606
Radius
Laser rod Ø =
θ_o
Thermal lens (f_{th})
D
Ideal
d_o
L_R
602
600

Fig. 6

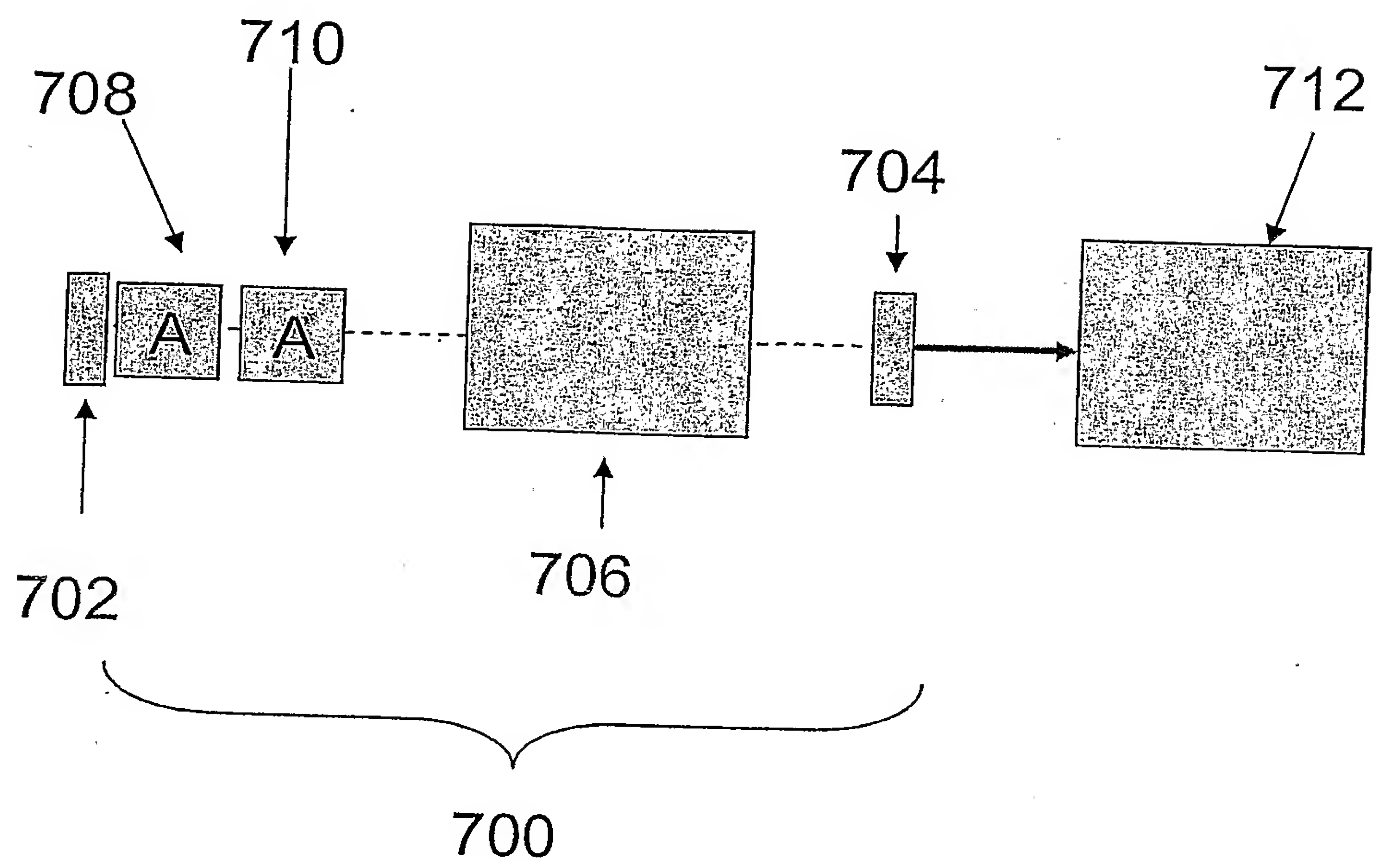


Fig. 7

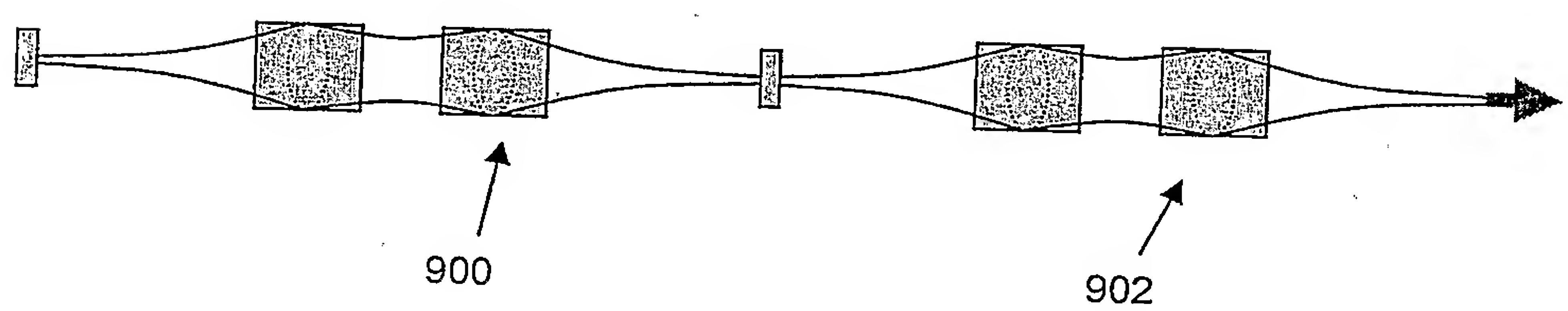


Fig. 8

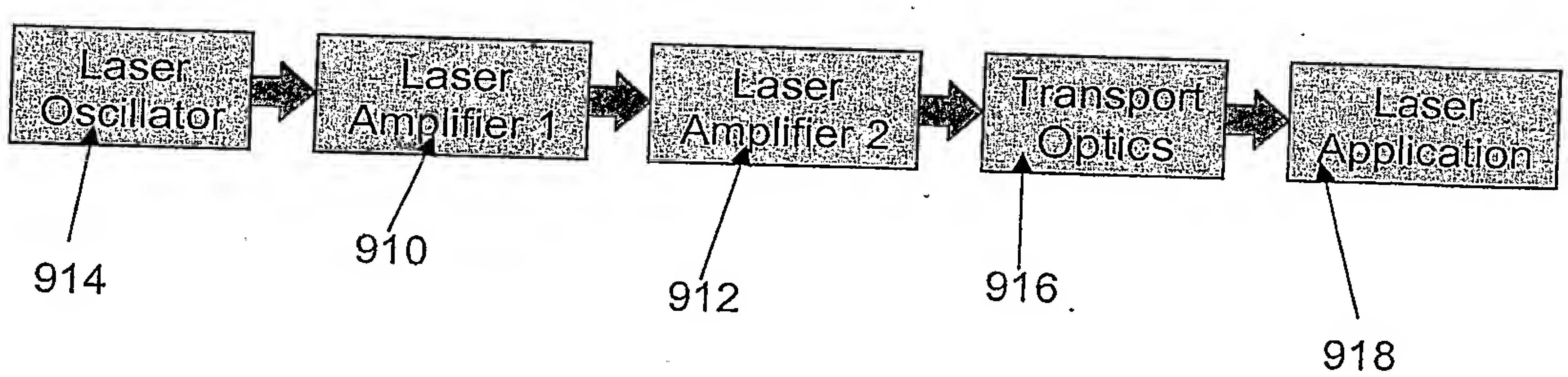


Fig. 9

PCT / GB 2005 / 000678

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